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Congestion pricing strategies to investigate the potential of route diversion on toll facilities using en-route guidance

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ABSTRACT

The application of intelligent transportation systems (ITS) technologies to facilitate the traffic mobility requires dynamic routing decisions. This study examines the effectiveness of Paramics, a microscopic traffic simulation model that uses a link-to-link shortest path algorithm to consider both updated link travel times and incident conditions detected through different traffic assignment techniques. This paper describes modeling of an urban highway network's traffic conditions to investigate potential route diversion through congestion pricing strategies on toll facilities in Orlando, Florida using Paramics. The experimental design included a multi-level factorial design with three qualitative variables and four response quantitative variables. The experiment's objective was to investigate different scenarios for reducing tolls on less congested roads (SR528 and SR417) and increasing tolls on more congested roads (SR408) to determine the impact on travelers' route choices and overall congestion in the network. The simulation results demonstrate that the Dynamic Feedback Assignment (DFB) led to a reduction in the average queuing delay and average travel time when compared to results from the Stochastic Assignment (SA). DFB significantly affected the percentage of diversion in the network. Drivers saved 10%–16% of travel time when DFB information was provided. Results also show that percentages of route diversion vary from one route to another and depending on the travel cost between specific origin-destination pairs. While drivers incorporate real time guidance information to maximize their own utility, not all drivers gain the same benefit. This was attributed to the limited extra capacity of the alternative routes and the longer travel distance. Combining congestion pricing strategies with traffic information maximize travel time benefits.

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1. Introduction

Simulation modeling is an increasingly popular and effective tool for analyzing a wide variety of dynamic problems, which are challenging to study by other means. Furthermore, the economic impact of traffic management is growing every day. Well-designed and well-managed highway systems could reduce the cost of transporting goods, cut energy consumption, and save countless hours of driving time. To reduce congestion, many countries have been investing heavily in building roads and improving their traffic control systems. ITS technologies present a positive step towards reducing congestion. ITS is implemented to optimize traffic assignment on the network by delivering static and dynamic information to drivers, thus allowing the drivers to adjust their travel routes to the least congested streets. Comprehensive research tools for quantifying the expected benefits from ITS are ongoing and extensive nowadays. In order to quantify the potential benefits prior to any major investment in development and deployment, the use of traffic simulation is regarded essential.

Computer simulation models are very valuable tools in investigating the potential of route diversion through ITS applications, as well as quantifying those benefits in a cost-effective manner. Such models can be used to evaluate modifications not only under existing conditions, but also under hypothetical scenarios that are difficult to observe in the real world. Such models can be used to predict route diversion based on demographic forecasts. Simulation models are designed to mimic the behavior of such systems. Properly, calibrated and validated models could transform these separate parameters and interactions to produce a detailed, quantitative description of system performance.

In this paper, a detailed examination of a severely congested Orlando network is analyzed and modeled using a powerful and popular traffic simulation model, Paramics. The dynamic re-routing strategies embedded in Paramics were utilized to address the benefits of such diversion strategies in response to different assignment techniques.

1.1. *Literature review*

Mahmassani and Jayakrishnan (1991) studied applications such as users' route choice dynamics in the case of lane closures of in a simulation environment. The results show that providing real time, in vehicle information to users could lead the network to reach a steady state at a faster rate than under the no-information case. A weighted average approach was suggested by Ben-Akiva et al. (1991) to represent drivers' perceived travel times as a function of the historic perceptions and the information travel time. This information model assumes that travel times are deterministic variables and thus doesn't account for the drivers' stochastic perceptions of travel times.

Another study of modeling traffic flows in networks of advanced traffic control and route guidance systems by Yang and Koutsopoulos (1996) using the Microscopic Traffic Simulator (MITSIM) on the A10 network in California with non-recurrent congestion caused by a 20 min incident was investigated. The case study demonstrates that an average 2%–4% of travel time savings is achieved when real time traffic information is provided to 30% of drivers. For drivers with viable alternative routes, real time route guidance is very effective, creating travel time savings of up to 18%.

Analysis of equilibrium dynamic assignments by Mahmassani and Peeta (1993) presents a large-scale study using the DynaSmart simulation assignment model to perform both user equilibrium (UE) and system optimal (SO) equilibrium calculations for a specified network. These calculations were completed over a range of traffic loading conditions, from unsaturated to over-saturated. This is an example of using a traffic simulation as a component of a larger model to perform a complex analysis of ITS initiative.

Al-Deek et al. (1989) discussed a study on the I-10 corridor project using Freeway Queuing Simulation Model version 8 (FREQ8) to evaluate the benefits of In-vehicle Information Systems (IVIS). In this study the FREQ model was used to simulate a section of the Santa Monica I-10 freeway in California. The study estimated delays, queues and travel times on the freeway based on scenarios of recurring and incidental congestion. The study produced a simulated corridor representative of the study section, which helped in testing the benefits of IVIS.

Gardes et al. (2002) developed a calibration process for the Paramics microscopic traffic simulation model to assess the model's ability to serve as a tool for evaluating freeway improvement strategies. Paramics was applied to the Interstate 680 in the San Francisco Bay Area, CA, providing a case study for an in-depth calibration of the model, as well as an evaluation of potential freeway improvement alternatives. Ma and Abdulhai (2002) also developed a genetic algorithm-based optimization approach to serve as a generic tool for calibrating microscopic traffic simulation model parameters.

Shaw and Nam (2002) concluded that micro simulation is a relatively new type of computer modeling that performs a detailed stochastic analysis of traffic operations on a series of roadway segments by simulating the motion of cars, second by second. The team evaluated the Paramics and Vissim packages. Both offered significant advantages compared to CORSIM, and Paramics is recommended as the basis for further simulation work. Fujii et al. (2004) found that, in Sweden, public acceptance of road pricing decreases as it is perceived as unfair and an infringement on freedom. Schmöcker et al. (2012) reported a survey investigating whether the same effects are found in the Asian country and region of Japan and Taiwan. The results indicated that fairness plays the same role. However, income had a direct effect on acceptance to Taiwan but not in Japan or Sweden. Bhatt et al. (2008) reported that in 1999, 90% of residents thought there was too much traffic in the capital, and 41% of survey participants believed that the best way to fund public transport improvements in London was congestion charge. Kim et al. (2013) investigated determinants of acceptability of environmental (carbon) taxation, for which trust in government and environmental concern are additional determinants. Carbon taxation is an extension of fuel taxes and may be viewed as transport pricing. Zheng et al. (2014) investigated the public acceptance of pricing schemes in

Australia using an ordered logit modeling approach. The survey data were analyzed to pinpoint important factors influencing people's attitudes to a congestion charge. They found that the amount of the congestion charge and financial benefits from implementing it have a significant influence on the respondents' support for the charge and their likelihood of their taking a bus to city areas.

1.2. Orlando network

The study network is located in Orlando, Florida. It is composed of two main diverging highways serving north–south corridor travel through Orlando, freeway interstate 4 (I-4) and toll road SR417 in addition to two east–west parallel toll roads SR408 and SR528, which are intersected with the above-mentioned highways from both ends. I-4 is a primary transportation corridor between the cities of Tampa and Daytona, and it serves commuter, commercial, and recreational traffic. The traffic data on the I-4 freeway section is collected from double inductance loops, which extend from "The Walt Disney World" area on the west side of the corridor to Lake Mary boulevard on the east side for a total length of 39 miles. This network is known for severe congestion during peak hours in the morning and evening. The congestion spans about 11 miles during the evening peak period in the central corridor area on I-4 as it is considered the main non-tolled road connecting the Orlando Central Business District (CBD) and the tourist attractions. The interstate carries an average annual daily traffic of 175,000 vehicles on segments in Orlando. So, for investigating a plausible mitigation to the congestion on the I-4 corridor, this research is implemented to determine plausible alternatives that can be used to alleviate the congestion during the peak periods.

The study network consists of 39 miles of I-4 that includes 59 on-ramps and 61 off-ramps, plus 55 miles of SR417, including 40 on-ramps, 42 off-ramps and 6 toll plazas. SR528 includes 15 miles of 22 on-ramps, 21 off-ramps, and 2 toll plazas, and SR408 includes 9 miles of 12 on-ramps, 13 off-ramps, and 1 toll plaza. The study period encompasses the evening peak period and extends from 4:45 p.m. to 6:00 p.m. The study network is shown in Fig. 1. The purpose of this paper is to study the effects of diversion of travelers from I-4 during peak periods to the toll roads. Also, congestion pricing and varied tolls on SR417, SR528, and SR408 are evaluated as part of the study on driver diversion and what affects decisions.

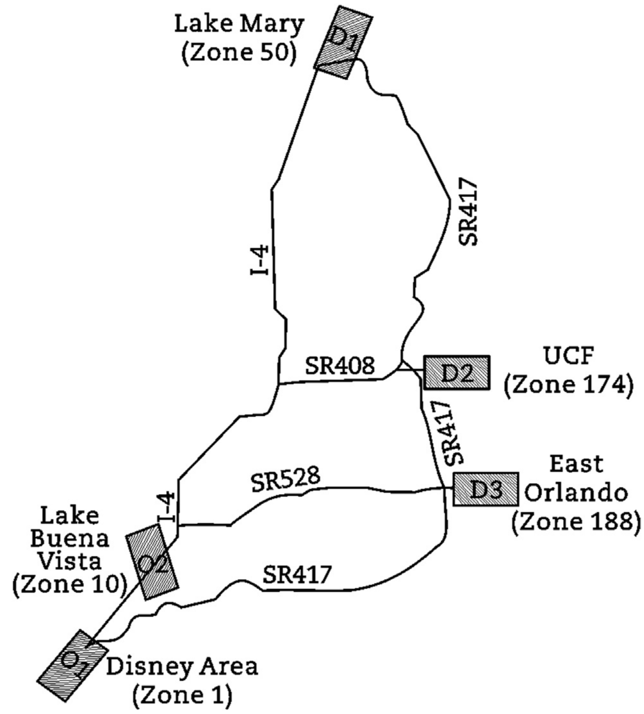

Fig. 1 – Orlando network.

2. Methodology and input data

2.1. Network geometry

The data collection process began with identifying data sources and types of data required for input into the simulation model. The Paramics model requires two main inputs: the road network data and travel demand data. The road network data is composed of the selected network's geometric layout, junction descriptions, lane markings, road widths, nodes, and links. Geometric data for the Orlando network is obtained from aerial photos. Paramics uses a CAD drawing as an overlay map to build the network. The ArcGIS 10 software tool is used to create a shape file that can be converted to a CAD drawing and then to a DXF format to serve as an overlay in Paramics. Arterials and minor streets in the limited access highway network are considered as origin and destination zones. Since they just process traffic from the origin to the Orlando network and from the network back to the destination, arterials and minor streets are not considered in the analysis. The complete network coded in Paramics include about 1600 nodes, 1600 links, 200 zones, and 9 toll plazas.

The network geometry is a major factor in vehicular behavior, and it can have a significant impact on vehicular speed. When the geometry is incorrect, vehicles may be forced to make sharp turns at the beginning or end of links, and a drop in vehicle speed would occur, leading to disruption in the traffic flow.

2.2. Travel demand

The second input is the travel demand data, which includes the origin/destination matrix. In this case, the matrix was constructed using Florida Standard Urban Transportation Model Software (FSUTMS), a travel demand software. This software is hosted by Florida Department of Transportation (FDOT). FSUTMS is a four-step travel demand forecasting and modeling program. As a major step in the four-step travel demand forecasting process, the trip generation predicts zonal trip ends for specific trip purposes based on land use and trip-maker characteristics. The prediction involves two sets of trips: those produced by an area (productions) and those attracted to an area (attractions). The results of the trip generation were used as an input to trip distribution, modal choice, and trip assignment models, which produce the origin/destination (O/D) matrix. This study uses select link analysis to assess the results. Thirty runs were carried out in FSUTMS, in which the user identifies an on-ramp as a link known by 2 nodes. This link was analyzed through out the Orlando network using the all or nothing assignment technique (AoN) to get the distribution of the vehicles from the on-ramp to different parts of the network specifically to an off-ramp. Using link analysis, the maximum number of links that can be analyzed at the same time is 5 and 150 on-ramps were analyzed during 30 runs resulting in an O/D matrix of 200×200 zones that serve as input to Paramics.

FSUTMS Orlando Urban Area Transportation Structure (OUATS) has a 2005 base year model with a forecast year model 2025. In order to get an intermediate year, such as the year under study (2011), interpolation can be used, as the growth rate formula is considered linear for the sake of simplicity. The estimated factor (0.68) was multiplied by the 2025 O/D matrix to achieve the target year 2011 O/D matrix, which was considered the preliminary O/D matrix for the network. Special assumptions were taken into consideration to fine tune of the O/D matrix prior to any Paramics runs, among:

(1) Trips from on-ramps to other on-ramps were eliminated (invalid in O/D matrices), and based on the fact that these vehicles were already counted as they exit the highway from off-ramp first. Through the arterials, they access the highway on-ramp again.
(2) Trips to a selected set of destinations are eliminated because some destinations are unreachable except arterials and, thus, off the limited access Orlando highway network.

2.3. Parameters calibration

Paramics has many parameters to be adjusted, as the default values were calibrated with United Kingdom (UK) traffic conditions. Paramics has about ten main sensitive parameters that affect calibration, i.e., mean headway, mean reaction time, perturbation which is a factor used to randomize the route cost perception to affect stochastic route choice, feedback which is a loop mechanism used to update travel time costs in order to influence route choice, the familiarity with the road, simulation time step details, aggressiveness, awareness of the drivers, signposting and the curve speed factor. Sensitivity analysis has been carried out for each parameter to determine its effect on the model output.

Several research teams have faced the issue of calibrating the mean target headway and mean reaction time when applying Paramics to a USA freeway facility. In a path research report published in May 1999, Abdulhai et al. (1999) from the University of California at Irvine reported a calibration effort on the southbound I-405 freeway, which is part of the California ATMS Test bed in Orange County, California. An empirical procedure was developed to calibrate the mean headway (H) and mean reaction time (R), and the best results were obtained for $H = 1.65$ s and $R = 0.42$ s. Finding appropriate values includes a two way dimensional search process. After combining several methods used in previous studies, $H = 1.00$ s and $R = 1.00$ s were found to produce the best results.

The simulation time steps determine when calculations are carried out during every second of simulation. The default time step is 2, which means that calculations are done every 0.5 s of simulation. For the Orlando network application, the time steps were increased from 2 to 4 steps per second, based on the fact that high density flows often require more time steps per second to operate in a freer manner.

Two parameter sets in particular, aggressiveness and awareness, were examined, as these significantly influence driver behavior and lane distribution. High aggression, for instance, causes drivers to accept a smaller headway. High awareness affects the use of a longer headway when approaching a lane drop in order to allow drivers in other lanes to merge more easily. During the test step, numerous runs with different distribution combinations were conducted until the outputs of lane usage improved.

On highway links, the default signposting distance is 2461 feet. It is possible to experience flow breakdown at the start of the signposting distance, with all vehicles noting the hazard simultaneously. Extending the mainline signposting values doesn't usually help. Longer signposting distances are considered more appropriate on USA highways, but in this case, fictitious bottlenecks were created due to longer signposting distances. Final adjustments of the signposting distances equal 400 and 200 feet, respectively. The first distance represents the location where vehicles are first made aware of the upcoming hazard, and the second represents the distance along the link that vehicles can react to the hazard by selecting the appropriate lane.

2.4. Generalized cost function

Each vehicle in Paramics chooses its route based on the perceived “cost” of that route, which is expressed in time (min). The default cost coefficient is calculated as $1.0 \times \text{Time} + 0.0 \times \text{Distance} + 0.0 \times \text{Toll}$, where time is the only factor. Thus, vehicles will choose their route solely based on the shortest estimated travel time. However, in reality, drivers also consider distance when choosing their route. Even if it means an overall faster trip, a driver in real life will usually not backtrack or travel a longer distance in the wrong direction to get to his destination. To account for this, distance coefficient is concluded.

Since the driver's perceived cost is always expressed in time (min), the “cost” of driving additional distance is expressed in adding the “cost” of an additional amount of time. This is expressed in minutes per mile. So if the distance coefficient is 1.0, and a driver is choosing between two routes when the travel time is the same, but with one route a mile longer, the driver will see that one extra mile as an extra minute of travel time. The toll factor works the same way. Paramics is equating the cost of paying a toll to a particular travel time. This is expressed in minutes per dollar, so if it is set to 1.0 min and the toll is one dollar, then the perceived “cost” of that toll would be 1 more minute of travel time. Therefore, a driver will only choose to pay the toll if alternative routes cost more than 1 additional minute.

2.5. *Travel costs*

Perturbation in Paramics is used to set the variability of route choices. Since real drivers do not have perfect knowledge, they will not always choose the absolute best route, and from driver to driver the perception of the best route will differ. Perturbation allows drivers to choose different routes and is called a stochastic route assignment. It can be thought of as an error percentage. If the perturbation is set to 10, then each driver will randomly encounter a route cost that may be up to 10% wrong. This way, two drivers traveling to and from the same O/D may choose a different route.

Parameters relevant to the route choice model, such as feedback, perturbation, and generalized cost coefficients, were used to control how a perceived cost is represented. As mentioned earlier, the travel costs represent a combination of factors that drivers take into account when choosing routes. In this study, default values for the free flow travel time and distance coefficients are 1.0 min and 0.0 min, respectively, and the toll price coefficient is assumed to be 4.0 min. Based on the 2011 Texas Transportation Institute (TTI) congestion report, Schrank and Lomax (2011) found that as average vehicle travel on freeways and arterial routes increased above congested levels, average speeds decreased in proportion to the level of increased traffic. By comparing average vehicles speeds on congested routes to average speeds on non-congested routes, Schrank and Lomax (2011) estimated that the additional time spent driving due to congestion on urban routes costs approximately $ 15 per hour. This means that each 4 min delay will cost one dollar. Therefore, the toll price coefficient assumes that a 4 min delay costs one dollar, which corresponds to $ 15 per hour. These calibration parameters were recommended as more precise in calibration and evaluation of route diversion using toll facilities in Paramics.

It was helpful to use 15 min as a warm up period for loading the vehicles on to the network, and to use different seed values on the same network would produce different simulation results. Seed splitting was used to improve the repeatability of the simulation runs to split the random number streams of the simulation model into 6 different or separate contexts. The random number streams were split into 6 separate parts, namely vehicle release rates, static vehicle type behavior, route choice, vehicle dynamics, tolls or link stop times, and incidents, respectively.

2.6. *Validation approach*

The purpose of the validation step is to confirm the applicability of the developed model. It is essential to test how closely the model behavior corresponds to the actual operation. As mentioned earlier, data sets were divided into two categories. The first set (2 d) was used in the calibration process. The second set (1 d) was used in the validation process. Typical traffic flow characteristics used in validation process included traffic volumes and queue lengths.

Three field data sets were collected covering variable traffic conditions in different days for the evening peak periods. Each data set consisted of thirty locations on the network known as master links. Field data for 2011 were collected for the I-4 from historical data of the website developed at the ITS lab at the University of Central Florida (UCF). Other field data for toll roads were gathered from the Orlando Orange County Expressway Authority (OOCEA) website. Three remaining links belonging to the turnpike were collected from the FDOT CD 2011. A statistical comparison between the three days was carried out using paired t-test and the results show that there was no significant difference between days. The second set (1 d) of the 3 d was used to validate the network. Simulation runs were conducted to compare the results to the real data.

Table 1 presents a summary of the comparison in total demand. In addition to the zone-by-zone outputs, the average value of the total demand volume obtained from the three data sets was calculated, and then compared to the result obtained previously in the calibration scenario.

Table 1 – Simulated versus real zone traffic generation.

Zone	Actual release counts	Simulated release counts	Relative error (%)	Zone	Actual release counts	Simulated release counts	Relative error (%)
1	2361	2321	1.69	18	0	0	–
2	1045	1108	−6.06	19	1072	1066	0.54
3	0	0	–	20	225	211	6.09
4	0	0	–	21	0	0	–
5	0	0	–	22	188	184	2.01
6	772	803	−4.07	23	431	422	1.97
7	0	0	–	24	0	0	–
8	0	0	–	25	1105	1120	−1.32
9	775	814	−5.05	26	0	0	
10	968	970	−0.25	27	549	555	−1.02
11	0	0	–	28	0	0	–
12	553	534	3.38	29	0	0	–
13	695	671	3.50	30	461	456	1.05
14	0	0	–	31	355	359	−1.11
15	0	0	–	32	295	292	1.08
16	960	950	1.06	33	0	0	–
17	0	0	–	34	380	366	3.81

(*continued on next page*)

Table 1 – (continued)

Zone	Actual release counts	Simulated release counts	Relative error (%)	Zone	Actual release counts	Simulated release counts	Relative error (%)
35	313	288	8.06	98	0	0	–
36	640	639	0.09	99	357	360	−0.93
37	534	529	0.90	100	384	394	−2.67
38	0	0	–	101	216	197	9.00
39	661	675	−2.13	102	174	165	5.09
40	600	583	2.87	103	189	169	10.39
41	0	0	–	104	0	0	–
42	0	0	–	105	682	677	0.77
43	391	386	1.31	106	0	0	–
44	639	622	2.63	107	439	438	0.16
45	345	362	−4.86	108	0	0	–
46	0	0	–	109	498	499	−0.25
47	14	16	−14.78	110	0	0	–
48	125	137	−9.92	111	482	515	−6.81
49	186	190	−2.07	112	0	0	–
50	1215	1142	6.03	113	496	515	−3.81
51	693	715	−3.19	114	0	0	–
52	478	478	0.01	115	421	436	−3.65
53	453	473	−4.31	116	0	0	–
54	627	632	−0.75	117	0	0	–
55	746	750	−0.51	118	0	0	–
56	325	310	4.53	119	0	0	–
57	327	318	2.81	120	172	161	6.50
58	0	0	–	121	206	196	4.77
59	535	532	0.65	122	137	127	7.26
60	535	525	1.80	123	144	147	−1.86
61	454	432	4.90	124	0	0	–
62	656	683	−4.12	125	277	275	0.78
63	18	22	−21.95	126	196	205	−4.60
64	435	415	4.69	127	98	100	−1.63
65	405	410	−1.21	128	185	195	−5.69
66	0	0	–	129	4	4	2.44
67	0	0	–	130	248	241	3.00
68	0	0	–	131	330	319	3.47
69	0	0	–	132	137	132	3.61
70	278	275	1.07	133	183	167	8.67
71	0	0	–	134	155	142	8.38
72	0	0	–	135	291	317	−8.90
73	273	270	1.12	136	308	301	2.11
74	0	0	–	137	15	8	45.80
75	586	609	−3.87	138	94	115	−21.95
76	0	0	–	139	0	0	–
77	463	472	−1.88	140	115	124	−8.01
78	278	292	−5.04	141	180	171	4.78
79	0	0	–	142	0	0	–
80	0	0	–	143	72	61	15.47
81	0	0	–	144	0	0	–
82	536	531	0.98	145	81	81	0.22
83	0	0	–	146	0	0	–
84	351	335	4.55	147	116	110	5.53
85	647	656	−1.39	148	84	74	11.53
86	410	414	−0.98	149	264	246	6.83
87	458	436	4.71	150	0	0	–
88	0	0	–	151	276	273	1.21
89	0	0	–	152	0	0	–
90	677	665	1.70	153	0	0	–
91	0	0	–	154	125	128	−2.70
92	143	150	−5.13	155	80	85	−6.86
93	0	0	–	156	0	0	–
94	209	225	−7.60	157	329	351	−6.75
95	0	0	–	158	248	249	−0.55
96	0	0	–	159	0	0	–
97	407	418	−2.77	160	226	219	3.23

Table 1 – (continued)

Zone	Actual release counts	Simulated release counts	Relative error (%)	Zone	Actual release counts	Simulated release counts	Relative error (%)
161	0	0	–	182	428	453	−5.83
162	0	0	–	183	274	274	−0.04
163	207	219	−5.98	184	251	250	0.37
164	192	187	2.54	185	294	318	−8.33
165	759	728	4.02	186	338	319	5.58
166	75	81	−8.55	187	244	241	1.04
167	390	407	−4.49	188	1099	1065	3.08
168	328	325	0.91	189	276	267	3.09
169	0	0	–	190	87	79	9.11
170	325	374	−15.18	191	137	147	−7.35
171	208	209	−0.35	192	134	133	1.10
172	0	0	–	193	375	365	2.60
173	3333	3296	1.12	194	390	390	0.08
174	904	897	0.82	195	273	288	−5.47
175	347	343	1.11	196	277	256	7.63
176	0	0	–	197	242	229	5.33
177	563	547	2.90	198	416	389	6.43
178	0	0	–	199	250	243	2.84
179	580	598	−3.15	200	468	504	−7.64
180	0	0	–				
181	412	424	−3.00	**Total**	**55,842**	**55,748**	**0.17**

Results indicated that the average error in the validation phase was acceptable and within 5% error according to the total volume released from each zone. The relative error was calculated for each master link to determine if error exceeds 15% threshold. Table 1 shows that the simulated volumes versus real volumes are within the recommended guidelines.

Another qualitative measure of performance for the validation process is the bottleneck locations. A snapshot of the Orlando network during the evening peak period is shown in Fig. 2, which features queuing conditions and bottlenecks in different parts of the network. The I-4 Central Corridor is backed up from John Young Parkway to Lee Rd. Holland East Plaza is also backed up on SR408, Curry Ford Plaza is backed up on SR417, and University Main Plaza is backed up on SR417.

2.7. Congestion pricing

The main objective of the Paramics application is to study the effect of congestion pricing strategies on route diversion in the Orlando network. Congestion pricing is the practice of charging motorists more to use a roadway or parking spot during periods of heaviest use. Model application in congestion pricing strategies include lowering tolls on SR417 and SR528, as well as increasing tolls on SR408 during evening peak of travel period. The hypothesis is that some travelers will switch from the congested, and more costly, toll road SR408, to the less congested, and lower costly, toll roads SR417 and SR528. This application was conducted using 48 scenarios that are explained in the next section.

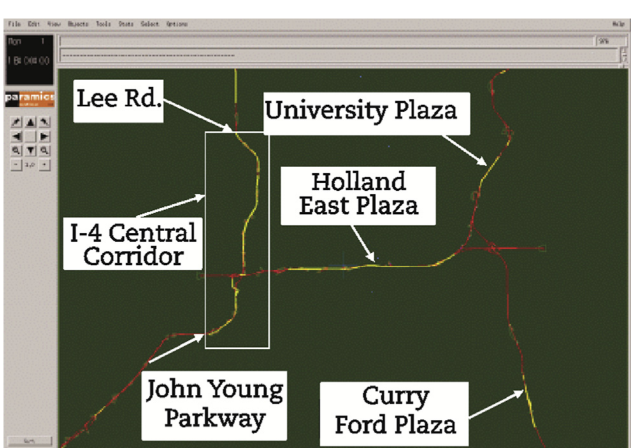

Fig. 2 – Queuing conditions on the Orlando network.

The travel cost on the links represents a combination of factors that drivers take into account when choosing routes. The most important factors are time, distance, and tolls. Congestion was priced according to the average cost of $ 15 per hour as discussed in the calibration section. The traffic volume variable has two levels (100% and 125%). The assignment method variable also has two levels (stochastic assignment and stochastic–dynamic feedback assignment). Stochastic Assignment (SA) accounts for variability in travel costs and assumes that the perceived cost of travel on each link varies randomly. Dynamic Feedback Assignment (DFB) assumes that drivers who are familiar with the road will re-route if information is provided. This is achieved by taking real time information from Paramics and updating the routing calculations. Other than their destination, vehicles in Paramics do not carry routing information beyond the next two links. There are several factors that affect the "costs" stored in routing tables in Paramics. One is feedback, which is where the "actual" costs encountered by vehicles traversing the network are used to periodically update the costs stored in the tables. Another factor is the perturbation which adds a random element to the costs. The number of tables stored in each node is wholly dependent on the restrictions within the network. Generally, the more restrictions there are within the network and the more complicated these restrictions are, the more routing tables will be required as different routes will be needed for different vehicle types and both familiar and unfamiliar drivers.

3. Design of experiment

The experiment in this study includes multi-level factorial design in which there were three qualitative variables and four response quantitative variables. Each of the three qualitative variables has a fixed number of levels. These variables comprise the cost, the traffic volume, and the assignment method. This experiment focuses only on the evening peak hour directions (Eastbound and Northbound) from 4:45 p.m. to 6:00 p.m. The cost variables include twelve different levels. Ten levels are comprised of increasing tolls on SR408, decreasing tolls on SR417 and SR528 as show in Table 2. There are 2 more levels that included an incident on I-4.

Table 2 – Scenarios for routing diversion of Orlando network.

Conditions on I-4	Scenario	Toll increased by	Toll decreased by	Assignment methods	Volume (%)
Recurring congestion	Base 1	–	–	SA	100
	Base 2	–	–	SA–DFB	100
	Base 3	–	–	SA	125
	Base 4	–	–	SA–DFB	125
	1	50% on SR408	–	SA	100
	2	50% on SR408	–	SA–DFB	100
	3	50% on SR408	–	SA	125
	4	50% on SR408	–	SA–DFB	125
	5	100% on SR408	–	SA	100
	6	100% on SR408	–	SA–DFB	100
	7	100% on SR408	–	SA	125
	8	100% on SR408	–	SA–DFB	125
	9	–	50% on SR528	SA	100
	10	–	50% on SR528	SA–DFB	100
	11	–	50% on SR528	SA	125
	12	–	50% on SR528	SA–DFB	125
	13	–	100% on SR528	SA	100
	14	–	100% on SR528	SA–DFB	100
	15	–	100% on SR528	SA	125
	16	–	100% on SR528	SA–DFB	125
	17	–	50% on SR417	SA	100
	18	–	50% on SR417	SA–DFB	100
	19	–	50% on SR417	SA	125
	20	–	50% on SR417	SA–DFB	125
	21	–	100% on SR417	SA	100
	22	–	100% on SR417	SA–DFB	100
	23	–	100% on SR417	SA	125
	24	–	100% on SR417	SA–DFB	125
	25	100% on SR408	50% on SR417	SA	100
	26	100% on SR408	50% on SR417	SA–DFB	100
	27	100% on SR408	50% on SR417	SA	125
	28	100% on SR408	50% on SR417	SA–DFB	125
	29	100% on SR408	100% on SR417	SA	100
	30	100% on SR408	100% on SR417	SA–DFB	100
	31	100% on SR408	100% on SR417	SA	125
	32	100% on SR408	100% on SR417	SA–DFB	125
	33	100% on SR408	50% on SR417 & SR528	SA	100
	34	100% on SR408	50% on SR417 & SR528	SA–DFB	100
	35	100% on SR408	50% on SR417 & SR528	SA	125
	36	100% on SR408	50% on SR417 & SR528	SA–DFB	125
	37	100% on SR408	100% on SR417 & SR528	SA	100
	38	100% on SR408	100% on SR417 & SR528	SA–DFB	100
	39	100% on SR408	100% on SR417 & SR528	SA	125
	40	100% on SR408	100% on SR417 & SR528	SA–DFB	125
Incident on I-4 between SR528 interchange and SR408 interchange	41	–	50% on SR417	SA	100
	42	–	50% on SR417	SA–DFB	100
	43	–	50% on SR417	SA	125
	44	–	50% on SR417	SA–DFB	125
	45	–	100% on SR417 & SR528	SA	100
	46	–	100% on SR417 & SR528	SA–DFB	100
	47	–	100% on SR417 & SR528	SA	125
	48	–	100% on SR417 & SR528	SA–DFB	125

The incident location was selected as I-4 (John Young Parkway) between SR408 and SR528 interchanges to study the purpose of studying the impact of increasing delay time on SR408 indirectly for the trips using I-4 and SR408. The incident duration was set for 45 min with a passing speed of 10 mph and opposing speed of 20 mph at the point of the incident.

The experiment evaluated all possible combination scenarios using the specified variables and levels with a 12 × 2 × 2 factorial design resulting in 48 different scenarios. The four response variables include the average queuing delay on the network, average speed, percentage of route diversion, and their associated travel times between specific O/D pairs. Table 2 represents all possible scenarios associated with each level of the three qualitative variables. In addition to the 48 scenarios, the base case scenario is associated with the volume and assignment method levels as well. In other words, there were 4 more base scenarios, 2 investigated at the volume levels (100% and 125%) and 2 investigated at the assignment methods levels (SA and SA–DFB) with no change in the cost levels. These 4 base scenarios are compared with all 48 scenarios to investigate the effect of the cost variable levels on the Orlando network. To investigate the impact of varying tolls on the Orlando network during the evening peak hour, 52 total scenarios including base scenarios were generated. In this analysis, four groups consisting of twelve different cost levels on the toll roads representing the evening peak hour were investigated using two assignment methods and two volume levels. Percentage of route diversion and average travel time were analyzed between specific O/D pairs.

Fig. 1 shows the locations and names of these O/D pairs. The five O/D pairs used in this analysis are as follows:

(1) O1D1 is from Zone 1 (Disney Area) to Zone 50 (Lake Mary).
(2) O1D2 is from Zone 1 (Disney Area) to Zone 174 (UCF).
(3) O1D3 is from Zone 1 (Disney Area) to Zone 188 (East Orlando).
(4) O2D1 is from Zone 10 (Lake Buena Vista) to Zone 50 (Lake Mary).
(5) O2D2 is from Zone 10 (Lake Buena Vista) to Zone 174 (UCF).

These specific O/D pairs were chosen because they represent the eastbound and northbound peak travel directions at the same time that travelers have access to alternative routes between their origin and destination. Each O/D pair and its associated alternative routes are explained in the route diversion analysis discussion.

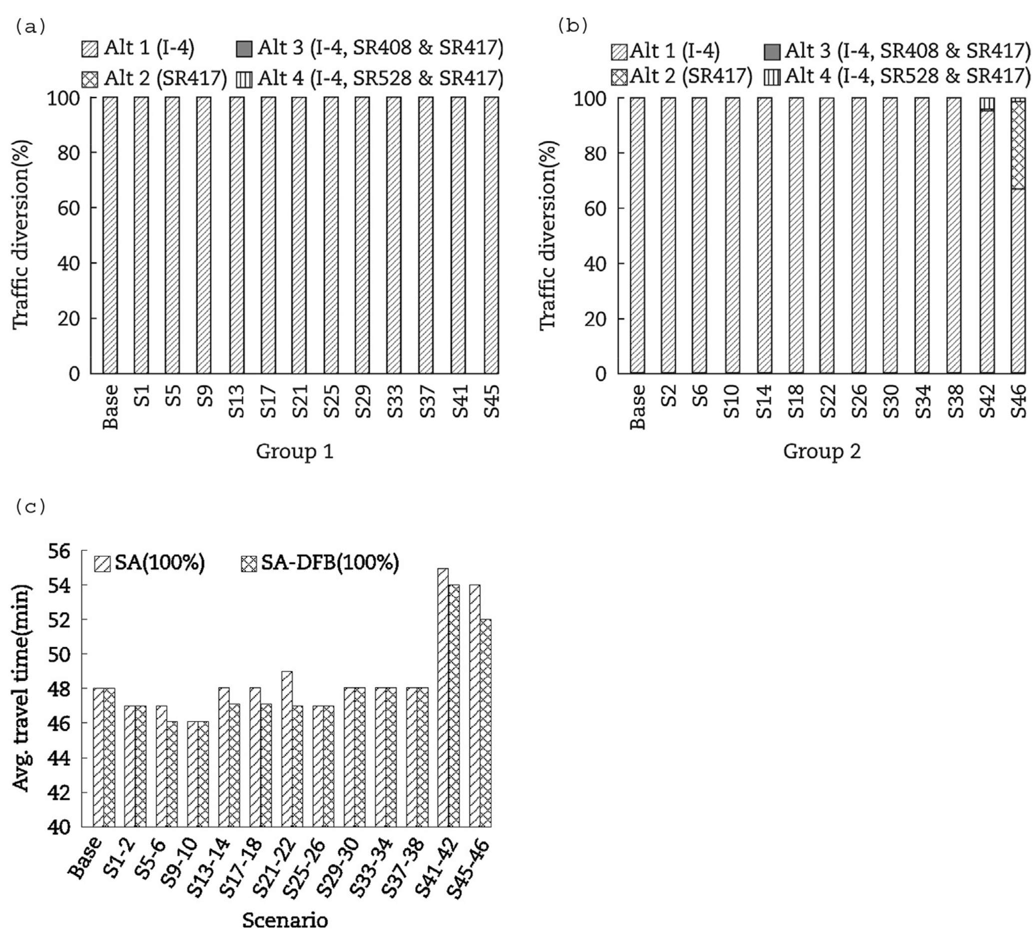

Fig. 3 – Percentage of diversion & average travel time for O1D1 (volume is 100%). (a) Stochastic assignment. (b) Stochastic–dynamic feedback assignment. (c) Average travel time comparison between Groups 1 & 2.

4. Route diversion analysis

Most drivers traveling from Disney Area (O1) or Lake Buena Vista (O2) to Lake Mary (D1) were found to have high propensity towards using I-4, even when reducing tolls and/or using DFB assignment at the base level of traffic volume (100%). This was attributed to the fact that I-4 is the only free route that directly connects the origin to the destination as mentioned before and it is the physical shortest path for these O/D pairs. Results also show that a diversion from I-4 to SR417 and/or SR408 for these O/D pairs occur only in the case of the incident on I-4 through DFB assignment, as shown in Figs. 3 and 4 in scenarios 42 and 46. Furthermore, drivers that diverted from I-4 to SR417 and SR528 did not gain significant travel-time savings. This was attributed to the capacity of the alternative routes and traveling distance, since the alternative routes have little extra capacity during the peak hour and are much longer.

On the other hand, congestion pricing (toll cost variations) with the DFB assignment shows significant impact to the diversion process, especially for the trips heading to UCF (D2) and East Orlando (D3). The DFB assignment caused diversion in most of the cases. The highest percentage of diversion occurred when the tolls on SR408 were doubled at the same time that tolls on SR417 were totally removed, as shown in Figs. 5 and 6 in scenarios 37–40. The percentage of diversion from SR408 to SR417 ranged from 25% to 100% for the UCF and East Orlando destinations. Increasing the tolls by 50% on SR408 alone did not encourage drivers to divert from it. The same conclusion was observed with the 50% decrease of tolls on SR528.

On the contrary, doubling tolls on SR408 at the same time as decreasing the tolls on SR417 and SR528 by 50% shows that drivers have a high tendency to use SR528 and SR417. Percentage of diversion from SR408 to SR528 and SR417 varied from 50% to 100%. However, the average travel time was relatively high in these scenarios compared to the base scenarios. This result shows that diverted vehicles cause a negative impact on some O/D pairs that primarily use SR528. Overreaction of drivers in diverting to SR528 through I-4 (100% diversion) increased the congestion on I-4 and SR528, causing a negative impact on these O/D pairs.

In addition, the alternative route through I-4, SR528 and SR417 is slightly longer than the route through I-4 and SR408. This indicates that, because users maximize their own utility while incorporating the real time guidance information, some drivers benefited while others were negatively affected. In some cases, such as when alternative routes are already operating at their capacities, this negative impact of real-time route information can offset the benefits achieved. Based on this analysis and the scenario results, tolls on SR408 should be

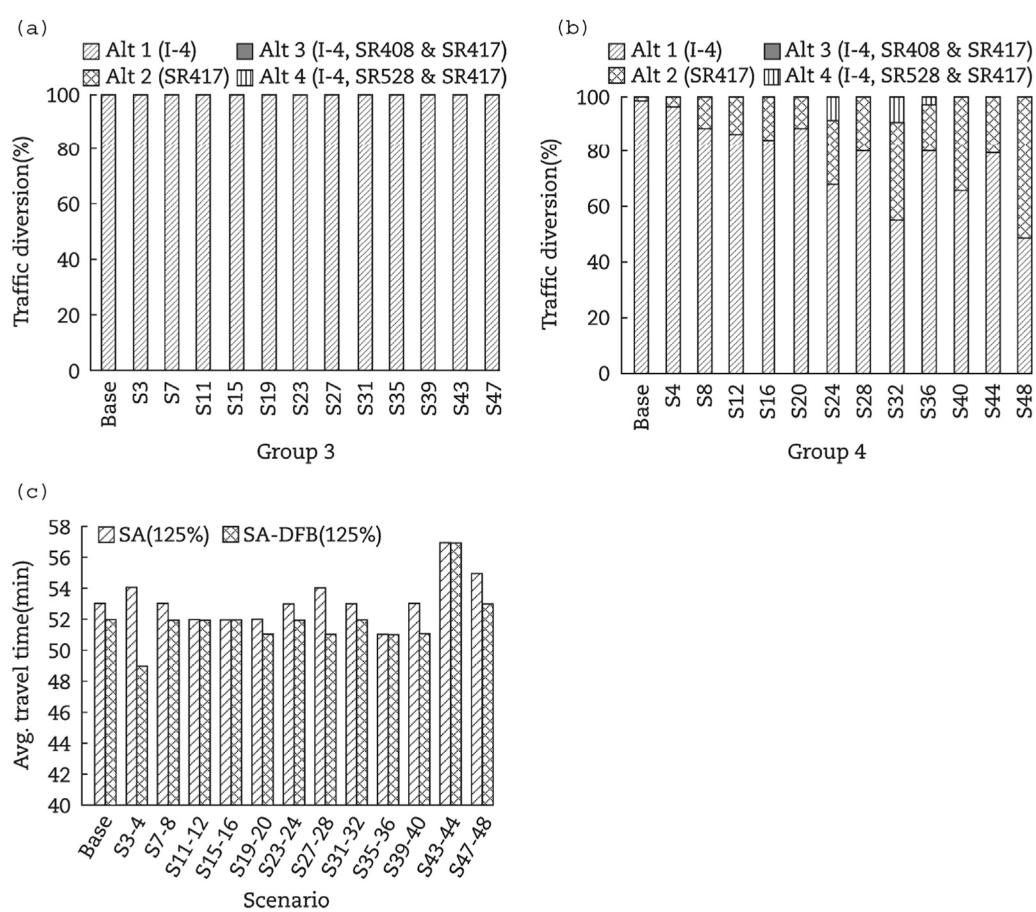

Fig. 4 – Percentage of diversion & average travel time for O1D1 (volume is 125%). (a) Stochastic assignment. (b) Stochastic–dynamic feedback assignment. (c) Average travel time comparison between Groups 3 & 4.

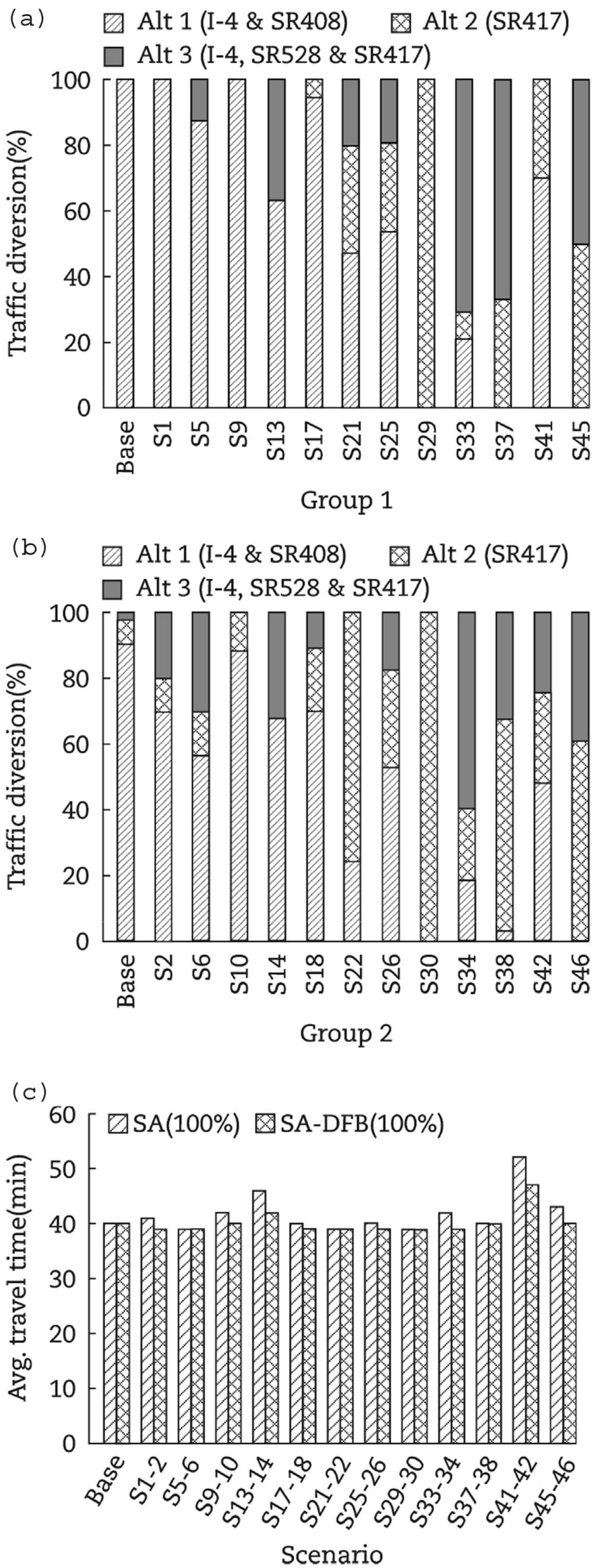

Fig. 5 – Percentage of diversion & average travel time for O1D2 (volume is 100%). (a) Stochastic assignment. (b) Stochastic–dynamic feedback assignment. (c) Average travel time comparison between Groups 1 & 2.

increased by 50%. At the same time the tolls on SR417 and SR528 should be decreased by 50%. This will alleviate some of the congestion on the Orlando network during the peak period and keep the network balanced without driver overreaction.

Overall, the average travel time was higher when traffic volume reached 125% compared to 100% traffic volume. Also, a 10%–25% increase in the network average travel time occurred when the volume on the network increased by 25%. The incident scenarios show a significant increase in the average travel time of the whole network except for the trips traveling from Disney Area to East Orlando. This was due to the absence of incident on the routes connecting this O/D pair. The percentage of time increase on the network due to the incident ranges from 10% to 56%. Compared to the case without guidance (SA), average drivers saved 10%–16% of travel time when DFB information was provided.

5. Conclusions

Several conclusions are drawn from the results of this study. Five O/D pairs were selected to analyze the percentages of route diversion on the Orlando network and their associated average travel times. The results show that percentage of route diversion varies from one route to another, depending on the travel time of the route connecting between the origin and destination. Also, drivers have a high propensity towards using routes that directly connects the origin to the destination. The travel cost of the links represents a combination of factors that drivers take into account when choosing routes. The most important factors are time, distance and tolls.

DFB significantly affects the percentage of diversion on the network, especially during high congestion at a traffic volume level of 125%. DFB assignment reduces the average queuing delay and the average travel time on the network in comparison to SA. This demonstrates the benefits of using Advanced Traveler Information Systems (ATIS) to inform drivers about current congestion locations so they may divert to an alternative. On the other hand, DFB assignment did not show a significant impact on the network average speeds, although a slight increase in the overall average speed of the network exists in most scenarios using the DFB assignment. But the increase was only within the range of 3%. This result does not contradict the impact of DFB assignment on the average travel time of the network. However the average travel time was analyzed between specific O/D pairs only when the speed analysis was conducted for the overall network performance.

Based on the results of this study, route diversion through ITS applications on the Orlando network through Paramics is effective in identifying the network's congested hotspots on the network. The paper also examines how DFB assignment helps to reduce the amount of time lost by the travelers during peak periods by providing real time information. This was achieved by allowing drivers to save money with the hypothesis of lowering the tolls on SR417 and SR528, while increasing tolls on SR408 during evening peak travel period. Furthermore some travelers switched from the congested and more costly toll road SR408 to the less congested and lower cost toll roads SR417 and SR528. Another main conclusion showed that because users maximize their own utility when

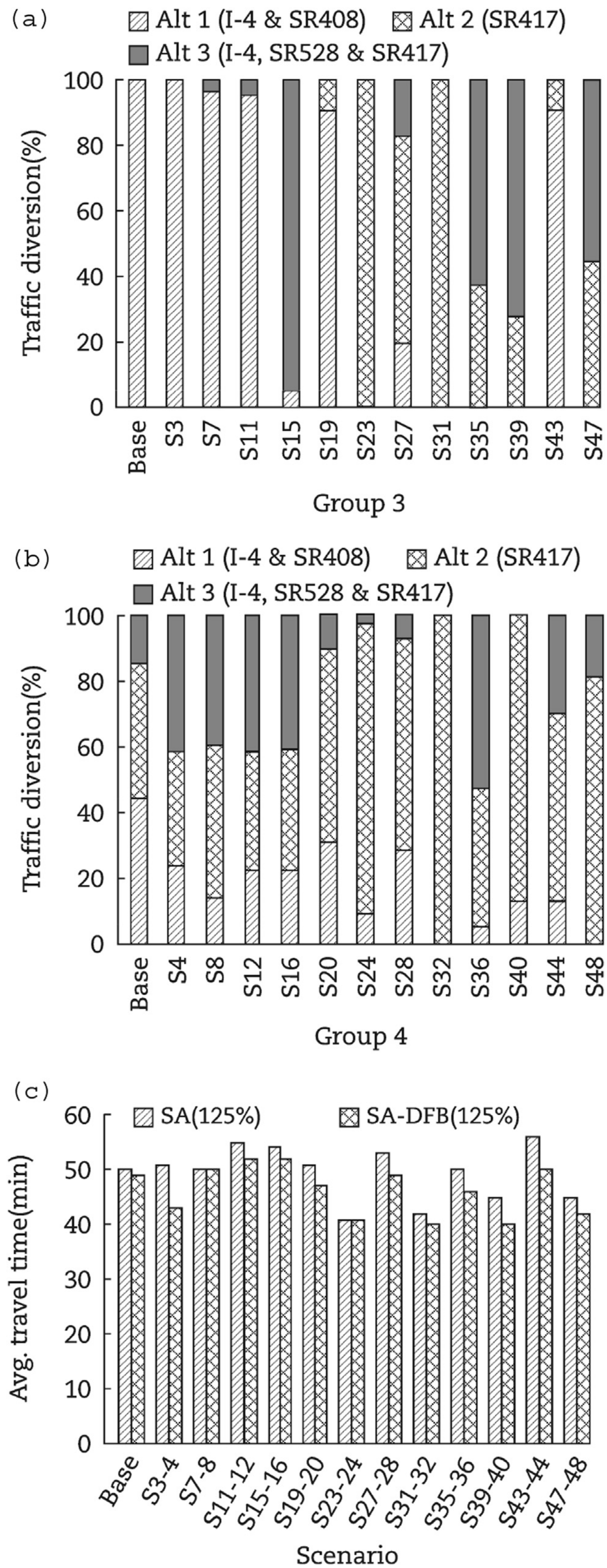

Fig. 6 – Percentage of diversion & average travel time for O1D2 (volume is 125%). (a) Stochastic assignment. (b) Stochastic–dynamic feedback assignment. (c) Average travel time comparison between Groups 3 & 4.

incorporating the real time guidance information, some drivers benefited while others were negatively affected. This was attributed to driver overreaction.

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